13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Probabilistic Approach to Prepare Input Models for Physics-based Ground Motion Simulation

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ABSTRACT: Accurate prediction of ground motion intensity and its variability is an important element in seismic hazard assessment. Physics-based ground motion prediction has become popular recently, given increasingly complex earthquake rupture and wave propagation modeling techniques and fast-growing computing capability. Physics-based ground motion prediction may contribute significantly to complementing empirical ground motion prediction equations (GMPEs), especially in near-source regions for large events, where we suffer from a lack of recorded ground motion data. However, it is also true that most input parameters required for modeling are not well constrained by observed geophysical data, and more importantly, the variability of the input parameters is not well quantified. It is essential to prepare reasonable input models and quantify their epistemic and aleatory uncertainty for successful application of the physics-based modeling to advanced seismic hazard assessment. I previously proposed to quantify the aleatory uncertainty of finite earthquake rupture processes in the framework of 1-point and 2-point statistics of key kinematic source parameters, such as slip, slip velocity, and rupture velocity. I developed a generalized source statistics model for the magnitude range of M_w 6.5–7.0 by analyzing a number (~150) of spontaneous dynamic rupture models and tested simulated ground motions against empirical GMPEs, following the broadband platform project of the Southern California Earthquake Center. This paper discusses various aspects of the potentials and challenges in the proposed earthquake source characterization, and subsequent earthquake source and ground motion modeling. When we combine realistic input models, whose epistemic and aleatory uncertainties are well quantified, with physics-based modeling, simulated ground motions may significantly contribute to advanced seismic hazard assessment.

Physics-based ground motion simulation has become feasible at least in the low-frequency band (<1 Hz), given advanced numerical modeling tools and fast-growing computing capability. To simulate seismic waveforms on the ground surface, we need to prepare input models for the earthquake source, crustal velocity, attenuation properties, and site conditions. In particular, it is difficult to prepare input rupture models that are physically self-consistent and cover the entire range of possible future earthquake scenarios. There have been several attempts to use dynamic rupture modeling for physics-based ground motion simulation, which turned out to be inefficient, given its high computational cost. Pseudo-dynamic source modeling has received attention as an alternative option. Song et al. (2014) proposed to develop a pseudo-dynamic source modeling method in the framework of 1-point and 2-point statistics of key kinematic source parameters. In this article, recent progress in the modeling method will be reviewed and several aspects about the potential and challenges of the method will be addressed.

1. PSEUDO-DYNAMIC SOURCE MODELING

Pseudo-dynamic source modeling retains the computational efficiency of kinematic modeling, but its physical characteristics are constrained by rupture dynamics. In particular, the correlation structures between kinematic source parameters are constrained by dynamic rupture models (Guatteri et al., 2004; Mena et al., 2012; Schmedes et al., 2013; Song et al. 2014; Trugman and Dunham, 2014). However, it is also important that the source modeling should be able to quantify the variability of finite source processes to sample the whole range of possible rupture scenarios for future events.

Song et al. (2014) proposed to quantify the variability of finite source processes with 1-point and 2-point statistics of earthquake source parameters. Then these statistics can be used to simulate physically self-consistent earthquake rupture scenarios and also effectively sample the variability of these scenarios.

2. SOURCE CHARACTERIZATION

The key element of pseudo-dynamic source modeling is the correlation structure between earthquake source parameters. Mostly, the correlation structure has been constrained by a number of spontaneous dynamic rupture models (Schmedes et al., 2010; Song, 2016). However, major input parameters, such as stress drop and fracture energy in dynamic rupture modeling, have not been well constrained by observed geophysical data. Song (2015a) demonstrated that source correlation statistics could be significantly disturbed by just perturbing the fracture energy distribution in the dynamic modeling. It seems necessary to test a wide range of input dynamic parameters to construct pseudo-dynamic source models by dynamic rupture modeling. It may be an alternative to preparation of dynamic input models by utilizing multi-cycle earthquake rupture modeling.

Pseudo-dynamic source models can also be constrained by kinematic source models obtained by inverting observed geophysical data (Song et al., 2009; Thingbaijam and Mai, 2006). However, we need to be careful when we use these models, given the level of uncertainty imposed in kinematic source inversion models. The variability of macroscopic source parameters, such as mean stress drop and mean rupture velocity, may also need to be treated carefully (Cotton et al., 2013; Causse and Song, 2015).

The currently proposed pseudo-dynamic source models with 1- and 2-point statistics allow us to model both the non-Gaussian 1-point statistics and the nonstationary probabilistic model. However, it is not straightforward to constrain these components of the pseudo-dynamic source model stably, given the current knowledge and data for earthquake rupture processes. There are trade-offs between increasing the complexity of a probabilistic pseudo-dynamic source model and retaining its stability. Determining these trade-offs may require a decision-making process to establish the appropriate level of complexity.

3. SOURCE MODELING

Once we construct a probabilistic pseudo-dynamic source model, stochastic earthquake rupture modeling can simulate individual rupture scenarios. Song and Somerville (2010) first proposed sequential Gaussian simulation, which was commonly used in the geostatistics community. Song et al. (2014) improved the modeling scheme by adopting Cholesky factorization of the covariance matrix constructed by input correlation models. In this way, it becomes feasible to perform stochastic simulation with a multi-variate correlation model that includes more than two parameters. However, Song et al. (2014) adopted eigenvalue decomposition to guarantee the positive definiteness of the covariance matrix, which is often computationally demanding for simulating large events. Lee and Song (2017) implemented nonparametric co-regionalization for permissible input correlation models to avoid the time-consuming eigenvalue decomposition.

4. GROUND MOTION MODELING

It is important to understand the effect of the earthquake source process on near-source ground motions, and there have been several attempts to tackle this issue recently (Imtiaz et al., 2015; Vyas et al., 2016; Crempien and Archuleta, 2017). The pseudo-dynamic source modeling with 1- and 2-point statistics has the potential to tackle this problem more efficiently because both earthquake source and ground motion modeling can be investigated in the same consistent framework of 1- and 2-point statistics, as shown in Figure 1. Song et al. (2014) initially investigated the effect of 1- and 2-point statistics of pseudo-dynamic source models on near-source ground motions. Fayjaloun et al. (2018) and Park et al. (2018) extended the modeling framework further.

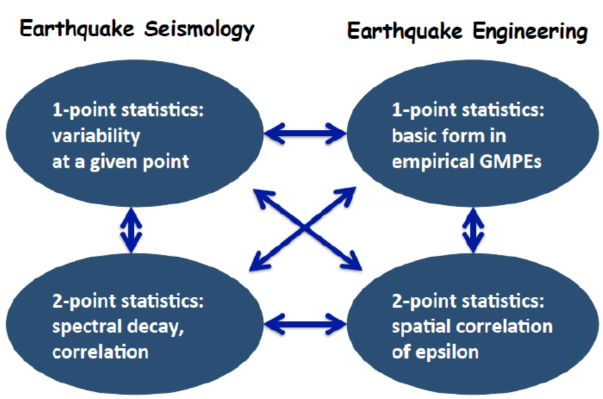

Figure 1. Consistency between source and ground motion modeling (Song, 2015b).

Recently the study of inter-period correlation of the Fourier amplitude spectrum of ground motions has received attention in the ground motion modeling community (Stafford, 2017; Bayless and Abrahamson, 2018). Because we can consider it to represent 2-point statistics of ground motion, it would be interesting to investigate the link between 1- and 2-point statistics of earthquake source parameters and 1-point (e.g., sigma) and 2-point (e.g., inter-period correlation) statistics of ground motion in a consistent framework.

5. CONCLUDING REMARKS

Physics-based ground motion simulation has become feasible for advanced seismic hazard assessment. Pseudo-dynamic source modeling with 1- and 2-point statistics has been proposed and tested for an efficient physics-based ground motion simulation scheme. The modeling platform still has issues, in particular to constrain more realistic input pseudo-dynamic source models. We are also limited to simulating high-frequency (>1 Hz) ground motion in a physics-based way. However, the pseudo-dynamic source modeling platform with 1- and 2-point statistics seems to have great potential for helping us understand the effect of earthquake source on near-source ground motion in a consistent framework.

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